

SIMULATION OF A SINGLE-PHASE ACTIVE POWER FILTER BASED ANN
CONTROLLER

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ABSTRACT

This project presents the employment of a single-phase active power filter (APF) to compensate harmonics generated by battery charger. The presence of the harmonics leads to various problems and poor power quality. The objectives of this project are to reduce the harmonic distortion and improve the power factor of the single-phase system with battery charger load. The operation of APF is verified using the simulations in Matlab/Simulink. Artificial neural network (ANN) control based shunt APF is compared to proportional-integral (PI) controller in order to regulate the DC-bus voltage and hysteresis current controller is employed to generate signal for switching purpose. The process is based on sensing line voltages, line currents, filter currents and DC side capacitor voltage. The error signal caused by the filter has been computed firstly. Then this error signal has been compensated using the controller and generates reference line current. The reference filter currents signal then obtained by subtracts the reference line current with the load current. This reference filter current is feed to the hysteresis current controller and compare with the sensed filter currents to obtain the switching signal for active power filter. Simulation results show that the ANN controller based shunt APF has better performance which has reduced harmonic distortion and improve system performance compared to the use of conventional PI controller.

Keywords: Shunt APF, PI controller, ANN controller, Total Harmonic Distortion (THD)

ABSTRAK

Projek ini membentangkan berkenaan penggunaan penapis kuasa aktif (APF) satu fasa untuk mengimbangi harmonik yang dijana oleh pengecas bateri. Kehadiran harmonik membawa kepada pelbagai masalah dan kemerosotan kualiti kuasa. Objektif projek ini adalah untuk mengurangkan gangguan harmonik dan meningkatkan faktor kuasa sistem satu fasa dengan beban pengecas bateri. Operasi APF disahkan dengan menggunakan simulasi di dalam perisian Matlab/Simulink. Pengawal rangkaian neural tiruan (ANN) berasaskan APF dibandingkan dengan pengawal PI untuk mengawal voltan DC dan pengawal arus histerisis digunakan untuk menjana isyarat pensuisan. Proses ini adalah berdasarkan pengesanan voltan talian, arus talian, arus penapis dan voltan sebelah DC kapasitor. Pertama, isyarat ralat yang disebabkan oleh penapis dikira. Kemudian isyarat ralat ini telah diberi pampasan menggunakan pengawal dan menjana arus talian rujukan. Isyarat arus penapis rujukan kemudiannya diperolehi dengan menolak arus talian rujukan dengan arus beban. Arus semasa rujukan ini disuapakan kepada pengawal arus histerisis dan dibandingkan dengan arus sebenar penapis untuk mendapatkan isyarat pensuisan untuk APF. Keputusan simulasi menunjukkan bahawa APF dengan pengawal ANN mempunyai prestasi yang lebih baik dimana telah mengurangkan gangguan harmonik dan meningkatkan prestasi sistem dibandingkan dengan penggunaan pengawal konvensional PI.

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CHAPTER 1

INTRODUCTION

This chapter will focus on the brief introduction of the project to be carried out. The important overview or description including the problem statement, project objectives, and project scopes are well emphasized in this part.

1.1 Overview

In recent years, the wide use of electronic devices such as personnel computer, smart phones, tablet, and even electric vehicle leads to employment of battery chargers. Battery charger is a device used to put energy into a battery by forcing current through it. In general, it consists of at least a diode to convert AC source to DC source. Diode is a non-linear device which generates harmonic in the power system line. The presence of harmonics in the system leads to various problems and poor power quality. These harmonics cause an increase in level of rms supply current, which results an increase of power loss, heating of equipment, voltage sags, power factor reduction and also deteriorates the quality of power [1]. The application of passive filter to overcome this problem causes a few problems such as it is large in size and has fixed compensation characteristics and they may fall in series resonance with the source impedance so that voltage distortion produces excessive harmonic currents flowing into the passive filter [1].

Active power filters (APF) offer a better solution for harmonic problems over passive filter [2]. The effectiveness of the filter depends on the topology and the inverter type [1]. The topology of the APF can be in shunt connected or in series

connected. Series connected APF can be connect before the load in series with the mains using a matching transformer to eliminate the voltage harmonics and to balance and regulate the terminal voltage of the load. Also it can be used to regulate the negative sequence voltage at the load. So the series APF works as a controllable voltage source. The drawbacks of this series connected APF is, it only compensates the voltage harmonics and another problem is for the short circuit in the load end. This short circuit current passes through the series transformer winding, which may overload the series transformer [1].

For this project, Shunt APF is employing to the system. Generally shunt APF is designed to eliminate the majority of the harmonic current orders and thus prevent significant harmonic voltages. As is defined in IEEE 519-1992, harmonic voltage is created when harmonic current travels through the impedance of the electrical system toward the lowest impedance point [2]. Thus the APF in shunt connected uses power electronic device to produce current with 180 degree phase shift to the harmonic current to eliminate the harmonic current. The shunt APF act as another source which generates harmonic current with the same magnitude but opposite in direction to the system.

This study has been focused on improvement of harmonic compensations and power factor on the AC supply side of the single-phase system with battery charger load. The APF consists of voltage source inverter (VSI) with DC capacitor as an energy storage device. The APF has two parts of controller which are voltage control loop (VCL) and current control loop (CCL). For VCL, artificial neural network (ANN) controller is used to regulate DC bus capacitor voltage instead of classical proportional-integral (PI) controller presented in [3] to provide harmonic current compensation and reactive power to the load. The DC bus capacitor voltage should be controlled to supply the power losses of filter on the system, providing that more effective filtering and reactive power compensation obtained [4]. In the CCL, hysteresis current control has been used to generate switching signals for the inverter. Hysteresis control technique is the most popular one for APF applications. Hysteresis current control is a method of controlling VSI so that the output current is generated follows the reference current waveform [5]. Trends and prospects in the system are presented and simulation results are carrying out by using Matlab/Simulink software.

1.2 Problem statement

Nowadays, AC power supply is used as a main supply for operation system. Therefore it will become a problem if the AC supply is not in its original condition due to the harmonic generated by the load especially a device which attached with the power electronic circuits. This harmonic will lead to the power quality problem which reduces the value of power factor. To solve this problem, harmonic filter is needed in order to remove them from the supply systems.

1.3 Objectives of the project

The main objective in this project is to compare the system response with shunt APF based PI controller and the system with shunt APF based ANN controller in order to reduce harmonic distortions and to improve power factor as well for the system with battery charger load. Therefore by using shunt APF topology the low supply harmonic current will be reduced and thus, power factor will be improved on the supply side as well. This project also aims to control and regulate the DC bus voltage of the single-phase APF and to obtain the switching signal for the APF to generate appropriate current compensations. Other objectives of this project are:-

- i. To develop a single-phase system with a battery charger load using Matlab/Simulink software.
- ii. To develop a shunt APF based PI controller and implemented in Matlab/Simulink software.
- iii. To develop a shunt APF based ANN controller and implemented in Matlab/Simulink software.
- iv. To develop a current control loop using Matlab/Simulink software.

1.4 Scope

The scope of this project is to study the characteristic and effect of the harmonics on non-linear load which is battery charger and to evaluate performance of the shunt APF based PI controller and the system with shunt APF based ANN controller in order to suppress the harmonics in the supply side through the simulation. In other words the aim of APF is to produce the harmonics current with the same magnitude but opposite in phase from the load. The simulation of this project is base on single-phase system. Other scopes of this project are:

- i. Use sine multiplication method for APF to extract reference supply current.
- ii. The switching control strategy is hysteresis current controller based on PWM signals.
- iii. The inverter system based on voltage source.
- iv. Shunt configurations of APF to the system.
- v. Using Matlab/Simulink software for system development.

1.5 Thesis outline

The thesis is organized into 5 chapters which are introduction, literature reviews, methodology, simulations and results analysis, conclusion and recommendation.

Chapter I discuss the background and general idea of the proposed project. Besides that, the objective and scope of the project are stated in this chapter.

Chapter II discuss the reviews of the literature which includes the principles of technique implemented in the active harmonic filters. The brief reviews of the control strategy used in the proposed filters also mentioned in this chapter.

Chapter III shows the research methodology of each design stage. The details of the topology are discussed in this chapter with the operations of the system.

Chapter IV presents the simulation results and analyse the compensation performance of the proposed filter subject to a battery charger load. The simulation results of the systems performance have been observed.

Chapter V states the conclusions and recommendations for future works that can be done to improve the systems.

CHAPTER 2

LITERATURE REVIEW

Literature review has been conducted prior to undertaking this project to obtain the information of the technology available and the method that used by other researchers on the same topic. This chapter provides the summary of literature reviews on key topics related to the active power filter.

2.1 Introduction

Mitigation or cancellation of harmonics can be done by using passive or active filters. Passive filters have been used for harmonic mitigation purposes for long time ago. They consist of capacitors, inductors, and resistors. However, this approach is unsuitable at the distribution level as passive filters can only correct specific load conditions or a particular state of the power system. The filter is unable to adapt to the changing system conditions. Passive filters can be divided into four categories which are lowpass, band-pass, high-pass, and tuned filters [6]. The increased severity of power quality problems and other problems associated with the passive filters such as large size and weight, higher cost, fixed compensation, and resonance problems with loads and networks have required a focus on a power electronic solution, that is, active filters. Nowadays, passive filters are used to cancel the switching frequency of active filters and high frequencies [7, 8].

2.2 Active filter

This chapter reviews the development of APF technologies. The advantage of the active filtering process over the passive filter is a factor of many researches to be performed on active power filters for power conditioning and their practical applications [9]. By implementing the APF for power conditioning, it provides functions such as reactive power compensations, harmonic compensations, harmonic isolation, harmonic damping, harmonic termination, negative-sequence current or voltage compensation and voltage regulation [10]. The main purpose of the APF installation by individual consumers is to compensate current harmonics or current imbalance as well as power factor improvements of their own harmonic-producing loads. Besides that, the purpose of the APF installation by the utilities is to compensate for voltage harmonics, voltage imbalance or provide harmonic damping factor to the power distribution systems [10].

The basic principle of APF is to produce specific currents components that cancel the harmonic components draw by the non linear load. The APF act as a harmonic source which is same in magnitude but opposite in direction to the harmonic caused by the non linear load. Reactive power required by the load also provided by APF and thus improve the power factor of the system. APF consists of an inverter with switching control circuit. The inverter of the APF will generate the desired compensating harmonics based on the switching gates provided by the controller. The crucial parts of this APF are to design the suitable controller and the filters configuration.

2.3 Classifications of active power filter

Based on topology, there are two kinds of active filters which are current source and voltage source active filters. Current source active filters (CSAFs) employ an inductor as the DC energy storage device. In voltage source active filters (VSAFs), a capacitor acts as the energy storage element. VSAFs are less expensive, lighter, and easier to control compared to CSAFs [11].

The most dominant type of active filter is the voltage source inverter-type active filter, which has been designed, improved, and used for many years and is now in the commercial stage [11,12]. Their losses are less than current source active filter and they can be used in multilevel and multistep configurations [11]. It consists of a DC-bus capacitor as energy storage and power electronic switches to generate harmonics currents according to the signal from controller.

2.4 Connections of active power filter

Active harmonic filter can be connected in several power circuit configurations. In general, they are divided into three main groups which are shunt APF, series APF and hybrid APF.

2.4.1 Shunt active power filter

This connection is most widely used in active filtering applications [3]-[5], [12]. It consists of a voltage or current source configurations. The voltage source inverter (VSI) based shunt APF is the most common type used today due to its well known topology and straight forward installation procedure [11]-[12].

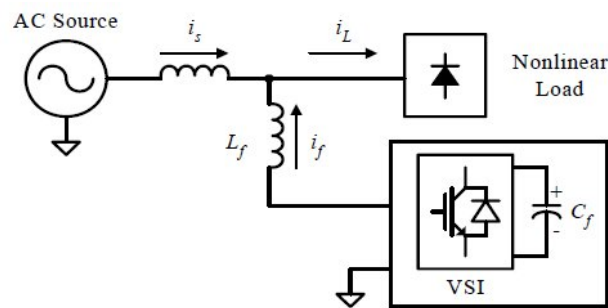


Figure 2.1: Configuration of a VSI based shunt APF

Figure 2.1 show a configuration of a VSI based shunt APF. It consists of a interfacing inductors (L_f) and VSI which is combination of a DC-bus capacitor (C_f) and power electronic switches. Shunt APF acts as a current source, compensating the

harmonic currents due to nonlinear loads. The operation of shunt APF is based on injection of compensation current which is equals to the distorted current, thus eliminating the original distorted current. This is achieved by generates the compensation current waveform (i_f), using the VSI switches. The shape of compensation current is obtained by measuring the load current (i_L) and subtracting it from a sinusoidal reference. The aim of shunt APF is to obtain a sinusoidal source current (i_s) using the relationship: $i_s = i_L - i_f$

2.4.2 Series active power filter

The series APF is shown in Figure 2.2. It is connected in series with the distribution line through a matching transformer [13], [14]. VSI is used as the controlled source, thus the principle configuration of series APF is similar to shunt APF, except that the interfacing inductor of shunt APF is replaced with the interfacing transformer.

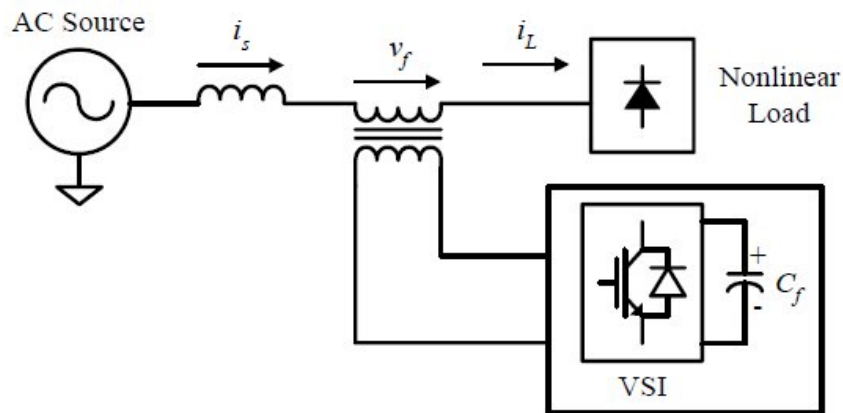


Figure 2.2: Configuration of a VSI based series APF

The operation principle of series APF is based on isolation of the harmonics in between the nonlinear load and the source. This is obtained by the injection of harmonic voltages (v_f) across the interfacing transformer. The injected harmonic voltages are added or subtracted, to or from the source voltage to maintain a pure sinusoidal voltage waveform across the nonlinear load. The series APF can be thought of as a harmonic isolator as shown in Figure 2.3. It is controlled in such a

way that it presents zero impedance for the fundamental component, but appears as a resistor with high impedance for harmonic frequencies components. That is, no current harmonics can flow from nonlinear load to source, and vice versa.

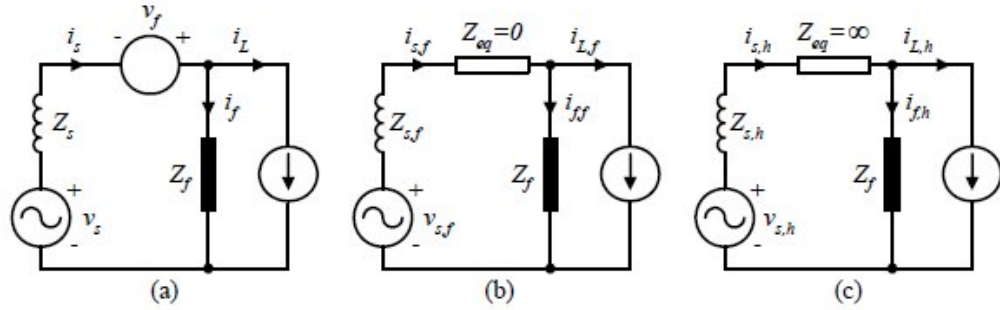


Figure 2.3: Operation principle of series APF: (a) single-phase equivalent of series APF, (b) fundamental equivalent circuit, and (c) harmonic equivalent circuit

Series APFs are less common than the shunt APF. This is because they have to handle high load currents. The resulting high capacity of load currents will increase their current rating compared with shunt APF, especially in the secondary side of the interfacing transformer. This will increase the I^2R losses [15]. However, the main advantage of series APFs over shunt is that they are ideal for voltage harmonics elimination. It provides the load with a pure sinusoidal waveform, which is important for voltage sensitive devices. With this feature, series APF is suitable for improving the quality of the distribution source voltage [12].

2.5 Reference signal estimations

Different kinds of control techniques are used to control APF. The reference signal to be processed by the controller is the key component that ensures the correct operation of APF. The reference signal estimation is initiated through the detection of essential voltage or current signals to gather accurate system variables information. The voltage variables to be sensed are AC source voltage and DC-bus

voltage of the APF. Typical current variables are load current, AC source current and compensation current of the APF. Based on these system variables feedbacks, reference signals estimation in terms of voltage/current levels are estimated in frequency-domain or time-domain for example [3]-[5], [12],[15] report on the theories related to detection and measurement of the various system variables for reference signals estimation. These reference signal estimation techniques can be divided into two groups which are frequency-domain and time-domain.

2.5.1 Frequency domain

Reference signal estimation in frequency-domain is suitable for single-phase system. They are mainly derived from the principle of Fourier analysis which Fast Fourier Transform (FFT) is applied to the captured voltage or current signal. The main drawback of this technique is the accompanying time delay in system variables sampling and computation of Fourier coefficients. This makes it impractical for real-time application with dynamically varying loads. Therefore, this technique is only suitable for slowly varying load conditions [12].

2.5.2 Time domain

Time-domain approaches are based on instantaneous estimation of reference signal in the form of either voltage or current signal from distorted and harmonic-polluted voltage and current signals. These techniques include instantaneous $p-q$ theorem, extension $p-q$ theorem, synchronous $d-q$ reference frame method, synchronous detection method and sine multiplication method [12], [16]. However, synchronous $d-q$ reference frame method and synchronous detection method are only suitable for three-phase system [17]-[19] while instantaneous $p-q$ theorem needs some modifications in order to make it applicable for single-phase system [20].

On the other side, both extension $p-q$ theorem and sine multiplication method are suitable for single-phase APF [3], [21]. The instantaneous active and reactive power of the load based on extension $p-q$ theorem are simpler compared with the $p-q$ theorem [22]. Sine multiplication method is based on the process of multiplying the nonlinear load current signal by a sine wave of fundamental frequency and

integrating the result to calculate the real fundamental component of nonlinear load current [23]-[25]. The difference between the nonlinear load current and this fundamental component is the command current for the APF.

2.6 Current control techniques

The aim of APF is to generate appropriate harmonic currents compensations. This can be achieved by generate appropriate gating signal for APF's inverter. The gating signal is based on the estimated compensation reference signals. The performance of an APF is affected significantly by the selection of control techniques [26]. A variety of control techniques, such as linear control, digital deadbeat control, hysteresis control etc., are implemented for the APF applications.

2.6.1 Linear control

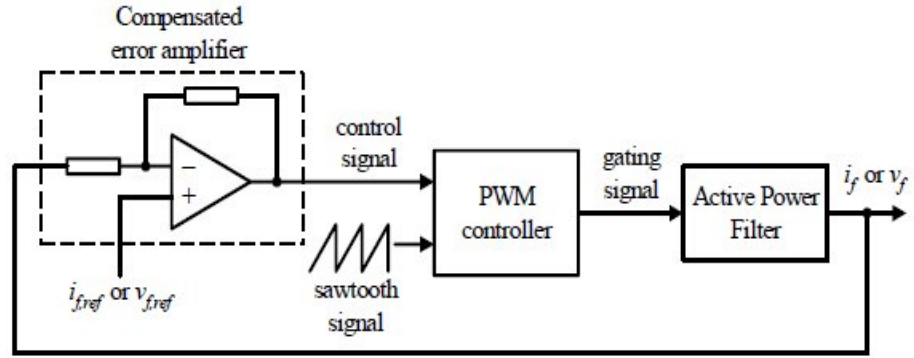


Figure 2.4: Linear control technique

Figure 2.4 shows the linear control of APF is accomplished by using a negative-feedback system. In this control scheme, the compensation current (i_f) or voltage (v_f) signal is compared with its estimated reference signal ($i_{f,ref}$ or $v_{f,ref}$) through the compensated error amplifier to produce the control signal. The resulting control signal is then compared with a sawtooth signal through a pulse width modulation (PWM) controller to generate the appropriate gating signals for the switching

transistors [21]-[25], [27]. The switching frequency is kept constant in linear control technique [12].

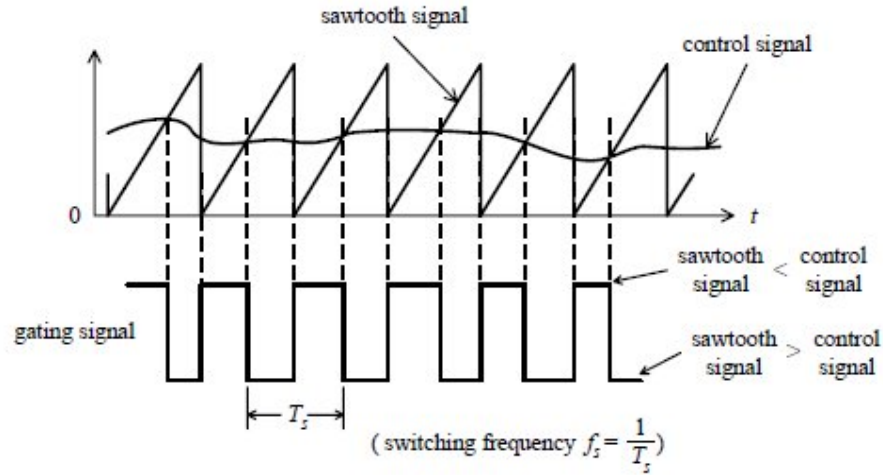


Figure 2.5: Gating signal for linear control

As shown in Figure 2.5, the gating signal is set high when the control signal has a higher numerical value than the sawtooth signal and low when the control signal has a lower numerical value than the sawtooth signal..

2.6.2 Hysteresis control

Hysteresis current control method is the most commonly proposed control method in time domain. This method provides instantaneous current corrective response, good accuracy, extreme robustness, good stability and allows fast current control [5], [12], [28]. The basic principle of current hysteresis control technique is that the switching signals are derived from the comparison of the current error signal with a fixed width hysteresis band. As long as the error is within the hysteresis band, no switching action is taken. Switching occurs whenever the error hits the hysteresis band. This control scheme is shown in Figure 2.6. The outputs of the comparator are switching gating signals to the inverter.

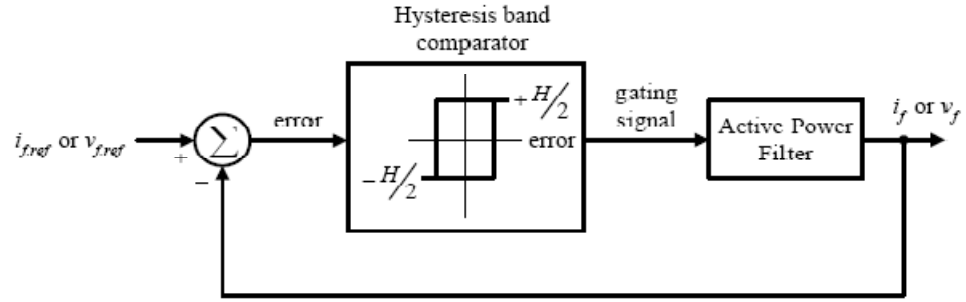


Figure 2.6: Hysteresis control technique

The APF is therefore switched in such a way that the peak-to-peak compensation current/voltage signal is limited to a specified band determined by upper band and lower band as illustrated by Figure 2.7. To obtain a compensation current with switching ripples as small as possible, the value of upper band and lower band can be reduced. However, doing so results in high switching frequency. Thus, increases losses on the switching transistors [12], [28].

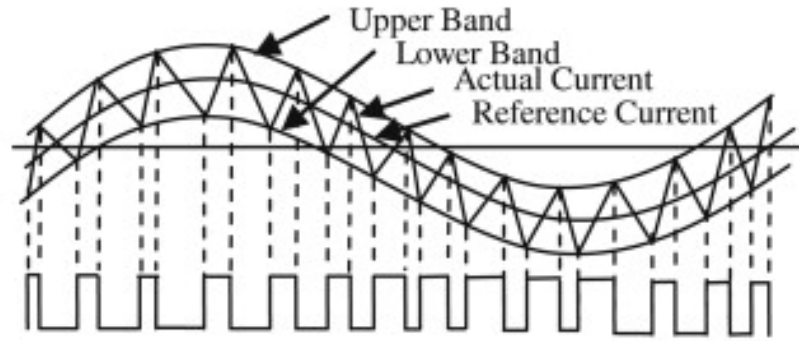


Figure 2.7: Gating signal generation

2.7 DC voltage regulation

The DC bus voltage must be regulated in order to set the amplitude of reference current for harmonic and reactive power compensation [28]. Practically, there are switching losses in the APF that increase with the increase in the active power or reactive power demand of the load. These losses are supplied by the capacitor, and its voltage drops. Similarly, the capacitor voltage will increase if the reactive or real

power demand of the load decreases. Hence, by monitoring the capacitor voltage, the real power supplied by the APF can be estimated and the amplitude of the fundamental active component of the supply current was estimated indirectly [29].

2.7.1 PI controller

Classically, PI controller has been used widely for shunt APF. The PI controller scheme involves regulation of the DC bus capacitor voltage to set the amplitude of reference current for harmonic and reactive power compensation [29]. However, PI controller approach requires precise linear mathematical model which is difficult to obtain. It also fails to perform satisfactorily under parameter variations, non-linearity and load disturbances [15].

2.7.2 ANN controller

Artificial Neural Networks (ANN) is biologically inspired models of computation. They are networks with elementary processing units called neurons massively interconnected by trainable connections called weights. ANN algorithms involve training the connection weights through a systematic procedure. Learning in ANN refers to searching for an optimal network topology and weights so as to accomplish a given goal-dictated task. Learning can be categorized as Supervised or Unsupervised. The Supervised learning refers to the presence of inputs and desired outputs for training. Unsupervised learning refers to determining the output categories or correlation inherent in inputs for training.

2.8 Research comparison

The comparison for each of the previous studies regarding the APF is summarized in Table 2.1.

Table 2.1: Comparison of each research

No.	Title	Method	Advantage(s)	Disadvantage(s)
1	Single-phase Active Power Filter for Harmonic Mitigation in Distribution Power Lines.	<ul style="list-style-type: none"> ▪ Shunt configuration ▪ FFT algorithm ▪ SPWM 	<ul style="list-style-type: none"> ▪ Less complex ▪ Low cost ▪ Eliminate low order harmonic 	<ul style="list-style-type: none"> ▪ Not applicable for high order harmonic ▪ Compensate single harmonic in a time
2	Analysis of Single-phase Active Power Filter	<ul style="list-style-type: none"> ▪ Shunt configuration ▪ P-Q theory ▪ Hysteresis control 	<ul style="list-style-type: none"> ▪ Feasible current harmonic detection ▪ Improve the power current 	<ul style="list-style-type: none"> ▪ Complicated
3	A Shunt Active Harmonic Filter Based on a Voltage Detection Method for Harmonic Voltage Control	<ul style="list-style-type: none"> ▪ Shunt configuration ▪ Voltage detection method ▪ D-q transformation 	<ul style="list-style-type: none"> ▪ Suppress voltage harmonic 	<ul style="list-style-type: none"> ▪ Complex control factor
4	Single-phase Resonant Converter with Active Power Filter	<ul style="list-style-type: none"> ▪ Shunt configuration ▪ Sine multiplication method ▪ PI controller ▪ Hysteresis control 	<ul style="list-style-type: none"> ▪ Simple ▪ Reduce current harmonic ▪ Power factor improvement 	<ul style="list-style-type: none"> ▪ Slow response ▪ DC bus voltage unstable
5	Design of Single-phase Shunt Active Power Filter Based on ANN	<ul style="list-style-type: none"> ▪ Shunt configuration ▪ Hysteresis control ▪ Sine multiplication method 	<ul style="list-style-type: none"> ▪ Reduce current harmonic ▪ Power factor improvement 	<ul style="list-style-type: none"> ▪ Complex mathematical modeling ▪

CHAPTER 3

METHODOLOGY

This chapter will describe the method that will be used for this project in order to achieve the desired objectives. This project development is divided into two parts. The first part represented the development of a system based on the PI controller and the second part will reflect the development of a system that used an ANN controller. Figure 3.1 compressed the project development.

The project developments shown in Figure 3.1 begin by the development of the single-phase system which consists of source and load. Extensive literature reviews were done on related knowledge to assist in any ways that it may. Such reviews are based on international publications, websites, and engineering books. The system requirement for the active power filter was then determined to proceed on this project.

The next step is followed by planning on the design of the single-phase active power filter system. The PI controller and ANN controller are responsible to regulate the DC bus voltage of the system. Both controllers have to be adjusted to obtain the best performance of the system. The results then have to be analyzed to ensure the best compensation of both controllers. If the results are not satisfied, the controllers should be adjusted due to their parameters.



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the load. The shunt APF also maintain the source signal in its original sinusoidal form by providing the reactive power required by the load, thus the source supply only active power to the system.

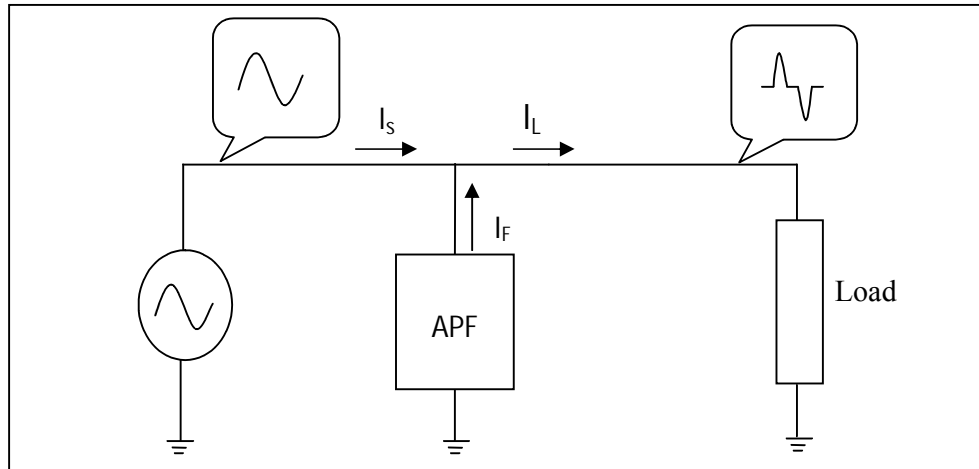


Figure 3.2: System configuration.

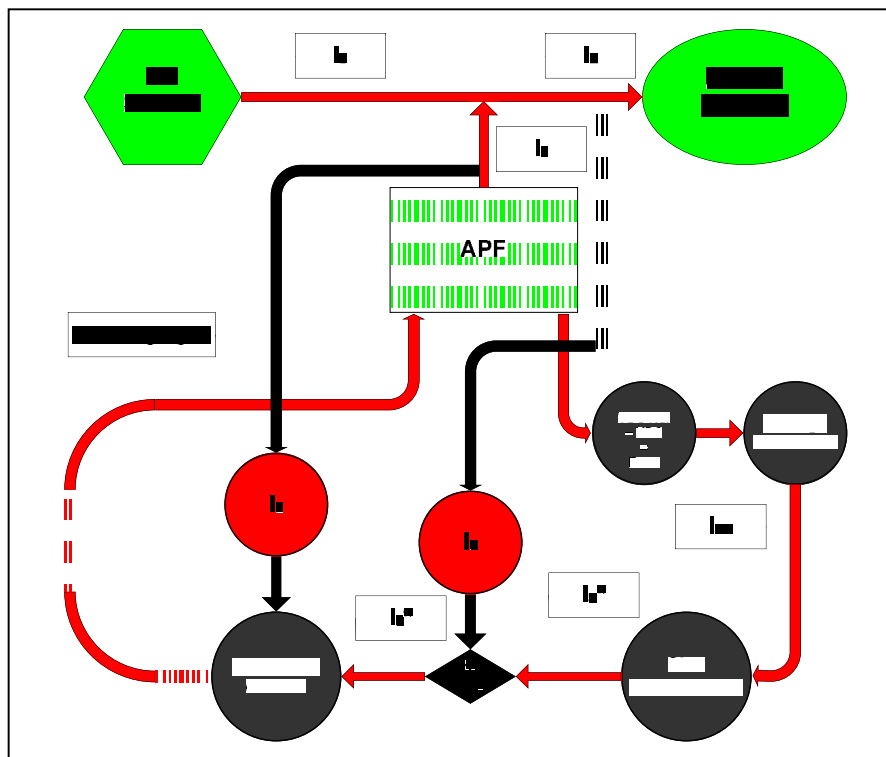


Figure 3.3 shows the system architecture of this project which the APF is mounted in parallel to the system. The proposed topology is presented in the following sections. It will primarily focus on the operation principle, system configuration and overall control system design. The system configuration and design that was based on pulse-width modulated (PWM) voltage source inverter (VSI). The filter was shunt-connected with the load that being compensated. The figure 3.2 also shows the concept of the harmonic current cancellation so that the current being supplied from the source was sinusoidal. Upon the voltage controller receive the error signal, the source voltage is extracted to generate unity sinusoidal signal to multiply with the peak DC signal from the voltage controller. The output of this operation will generate reference source current, I_s^* . At this point, the reference source current is removed from the detected load current, I_L to extract reference filter current, I_F^* . This allows the proposed active power filter to produce the output current, I_F according to the reference current I_F^* . These currents are then fed into hysteresis controller to generate the switching pattern of the VSI. Power switches in the inverter will operate according to the signals in order to produce the desired harmonic signals. This inverter uses dc capacitors as the supply and can switch at a high frequency to generate a signal which will cancel the harmonic from the nonlinear load.

3.2 Reference compensations current

The performance of an active power filter depends on many factors, but mainly on the selected reference generation scheme [26]. If the voltage of the line supply is a pure sinusoidal waveform, the instantaneous value of the voltage can be represented as in Equation 1.

$$V_{in} = V_s \sin(\omega t) \quad (1)$$

The unit vector for input voltage, $u(t)$ is generated as in Equation 2.

$$u(t) = \frac{V_{in}}{V_s} \quad (2)$$

Instantaneous value of total reference active current is obtained by multiplying the peak value of reference supply current i_{dc} with an unity sinusoidal signal, $u(t)$ which

is obtained from the line supply voltage at the fundamental frequency as in Equation 3.

$$I_s^*(t) = i_{dc} * u(t) \quad (3)$$

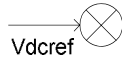
Finally, the reference compensation current of the active power filter is calculated by subtracting the instantaneous value of the total active current from the total load current in Equation 4.

$$I_F^*(t) = I_s^*(t) - I_L(t) \quad (4)$$

3.3 Control scheme

The aim of shunt APF is to obtain a harmonic compensation current (I_F) using the relationship as given in Equation 5, where I_s is the active component of the load current which is in phase with the source voltage at the fundamental frequency and I_L is the load current [12].

$$I_F = I_L - I_s \quad (5)$$



3.3.1 Voltage controller

Under loss free situation, the shunt APF need not provide any active power to cancel the reactive and harmonic currents from the load. These currents show up as reactive power. Thus, it is indeed possible to make the DC-bus capacitor delivers the reactive power demanded by the proposed shunt APF. As the reactive power comes from the DC-bus capacitor and this reactive energy transfers between the load and the DC-bus capacitor (charging and discharging of the DC-bus capacitor), the average DC-bus voltage can be maintained at a prescribed value. However, due to switching loss, capacitor leakage current, etc., the distribution source must provide not only the active power required by the load but also the additional power required by the VSI to maintain the DC-bus voltage constant. For the successful operation of APF, capacitor voltage should be at least 1.5 times of maximum line-to-line supply voltage [30]. For this project, the line-to-line supply voltage is 240V. Hence the minimum value of capacitor voltage that needs to be regulated is calculated as in Equation 6.

$$\begin{aligned}
 V_{DC} &= 1.5 \times \sqrt{2} \cdot V_s \\
 &= 1.5 \times \sqrt{2} \cdot (240) \\
 &\approx 510V
 \end{aligned} \tag{6}$$

In this project, there are two types of voltage controller will be discussed and their performance will be compared. The controllers that being used for this project are proportional-integral (PI) controller and artificial neural network (ANN) controller.

3.3.1.1 PI controller

Classically, PI controller has been used widely for shunt APF. The PI controller scheme involves regulation of the DC bus capacitor voltage to set the amplitude of reference current for harmonic and reactive power compensation [29]. However, PI controller approach requires precise linear mathematical model which is difficult to obtain. It is also fails to perform satisfactory under parameter variations, non-linearity and load disturbances [15]. Figure 3.5 shows the control algorithm usually used in literature [3], [7], [13], [17], [26].

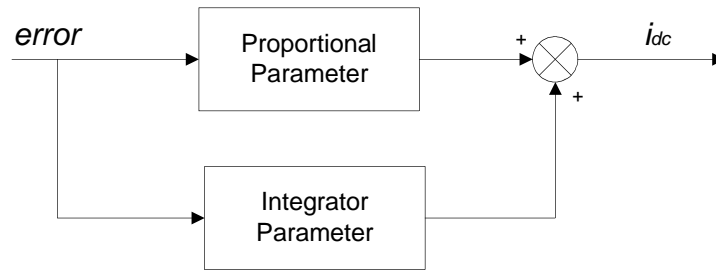


Figure 3.5: PI control algorithm

A PI controller used to control the DC-bus voltage is shown in Figure 3.5. Its transfer function can be represented as:

$$H(S) = K_p + K_i/S \quad (7)$$

Where K_p is the proportional constant that determines the dynamic response of the DC-bus voltage control, and K_i is the integration constant that determines the settling time. If K_p and K_i are large, the DC-bus voltage regulation is dominant, and the steady-state DC-bus voltage error is low. The proper selection of K_p and K_i is essentially important to satisfy above mentioned two control performances [31].

3.3.1.2 ANN controller

To design the ANN control some informations about the plant is required. Basically, the numbers of input and output neuron at each layer are equal to the number of input and output signals of the system respectively. Further the number of hidden layers and the total neurons is depended on the complexity of the system and the required training accuracy [16]. Based on the type of the task to be performed, the structure of the proposed controller is as shown in Figure 3.6.

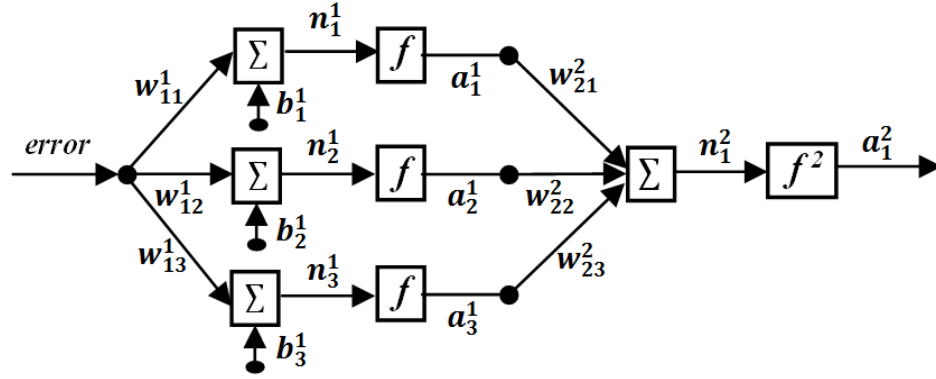


Figure 3.6: Proposed control algorithm

The controller consists of input layer, hidden layer and output layer. Based on number of the neuron in the layers, the ANN controller is defined as a 1-3-1 network structure. The first neuron of the output layer is used as a voltage reference signal ($a_1^2 = m_f$). The connections weight parameter between j^{th} and i^{th} neuron at m^{th} layer is given by w_{ij}^m , while bias parameter of this layer at i^{th} neuron is given by b_i^m . Transfer function of the network at i^{th} neuron in m^{th} layer is defined by [32]:

$$n_i^m = \sum_{j=1}^{S^{m-1}} w_{ij}^m a_j^{m-1} + b_i^m \quad (8)$$

The output function of neuron at m^{th} layer is given by:

$$a_i^m = f^m(n_i^m) \quad (9)$$

Where f is activation function of the neuron. In this design the activation function of the output layer is unity and for the hidden layer is a tangent hyperbolic function given by:

$$f^m(n_i^m) = \frac{2}{1 + e^{-2n_i^m}} - 1 \quad (10)$$

Updating of the connection weight and bias parameters are given by:

$$w_{ij}^m(k+1) = w_{ij}^m(k) - \alpha \frac{\partial F(k)}{\partial w_{ij}^m} \quad (11)$$

$$b_i^m(k+1) = b_i^m(k) - \alpha \frac{\partial F(k)}{\partial b_i^m} \quad (12)$$

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